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Final Technical Report

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Summary

We completed a resurvey of our GNSS benchmark network in the northern San Francisco Bay Area ("North Bay") in the summer of 2018. In total, 78 sites were measured, mostly in Marin, Sonoma and Napa Counties, targeting the major active faults in the region (i.e. the San Andreas, Rodgers Creek and Green Valley faults) as well as the area surrounding the West Napa fault, the source of the 2014 South Napa earthquake. These data were processed using the GAMIT/GLOBK software and we present here updated GNSS velocities from that effort, along with updates on the condition of various benchmark sites. We also committed some effort to a response to the 2019 Ridgecrest earthquake, both in terms of survey data collection and processing, on which we also report here.

The July-August 2018 GNSS survey

Our first task during this project was to collect more survey-mode GNSS measurements across our network of sites in Marin, Sonoma and Napa Counties, California. We conducted the survey in the field area over 9 days from July 31 to August 8, 2018, using equipment from UC Riverside and borrowed from UC Berkeley. We carried out the survey in two groups of two people each, one led by PI Funning with UCR graduate student Jerlyn Swiatlowski and the other led by PI Floyd with UCR graduate student Rachel Terry. For efficiency, the former group concentrated their efforts on the area between Napa and Sonoma, up the CA-101 corridor and towards the Pacific coast near Point Arena; the latter group concentrated on the coastline from Vallejo and American Canyon to Jenner and inland throughout Marin County. We measured 78 sites in total, almost all for between 18 and 26 hours (Figure 1).

One motivation for the resurveying of our network is the remeasurement of sites affected by the 2014-08-24 South Napa earthquake, which showed rapid and continuing post-earthquake motion from the data collected in the week (e.g. Floyd et al., 2016; Final

Technical Report for USGS Award G14AP00027 at https://earthquake.usgs.gov/cfusion/external_grants/reports/G14AP00027.pdf). In the intervening years, more measurements have been made at these sites and our most recent measurements now provide four years of measurements over a fairly dense survey network to supplement the relatively sparse local continuous network.

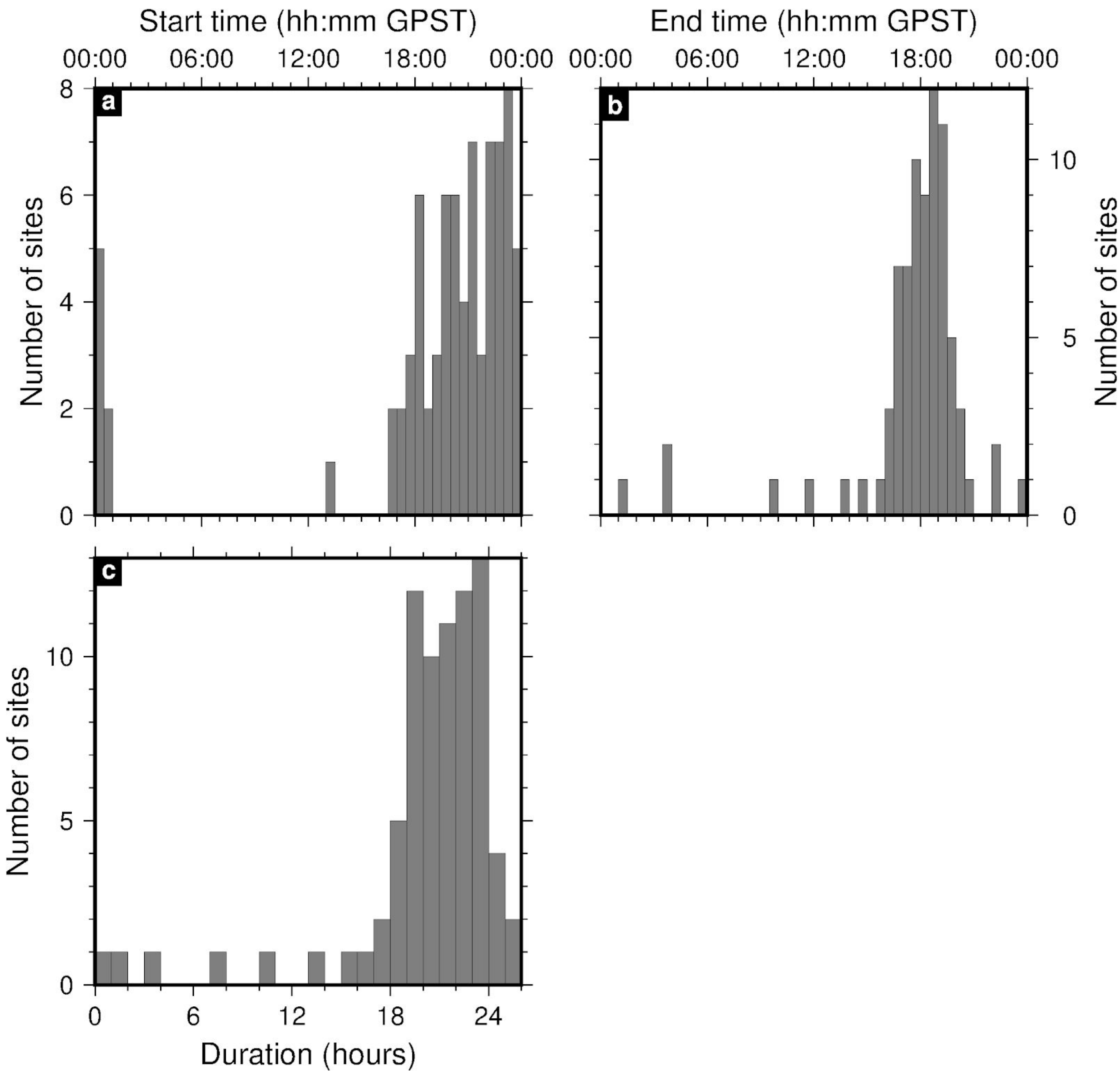

Figure 1 *Summary of the July-August 2018 survey site occupations. (a) Distribution of occupation start times in GPS Time (GPST). The local time of the survey was Pacific Daylight Time, seven hours behind GPST. (b) Distribution of occupation end times. (c) Distribution of occupation durations. The few sites for which we acquired less than 6 hours of data were those that had power problems or were disturbed, which required truncation of their data files, except for MONP, which was occupied in two shorter sessions rather than one longer session (see Table 2).*

Survey mark status and data archiving

We discovered that site 5020, near the gate at the Fish Docks in Point Reyes National Seashore, is now overgrown by the tree immediately to its north and no longer suitable for satellite observation. So we instead measured site 502M, just to the south and up the hill from 5020 at the fork in the road near the parking lot, and we equate the velocities in our solution presented later in this report.

All GNSS data collected during this survey is archived and publicly accessible at UNAVCO (Floyd and Funning, 2019, "North San Francisco Bay Area 2018 - Marin, Sonoma and Napa Counties", doi:10.7283/BB35-CW22). Raw and RINEX files plus scanned copies of our field log sheets are included in the files available there.

The log sheets note unusual instances at four sites occupied during the survey, which must be considered for any future user of the data. These are summarized in Table 1, below.

Table 1 *Summary of sites whose data collection was short or had to be truncated due to reported antenna disturbance or receiver problems.*

Site affected	Time occurred	Reason
6300	2018-08-07T03:52:00 GPST	Antenna disturbed; time determined by epoch-by-epoch analysis using `track`
MONP	N/A	Two shorter occupations instead of one longer occupation
TRAN	2018-08-01T19:22:30 GPST	Receiver appended the following site's (04NF) observations to this raw file for TRAN
X134	2018-08-07T01:16:00 GPST	Apparent power failure after 54 minutes

Many sites were also noted to be slightly off-center at the end of the occupation, presumably due to heat expansion of the supporting tripod, or disturbance by wind or some other external influence. These offsets are summarized in Table 2, below, with our proposed average antenna offset to include, which should also be considered when using the data we collected.

Table 2 *Summary of horizontal antenna offsets recorded when equipment was removed, for use in RINEX headers. The Δe (east) and Δn (north) columns are calculated by dividing the offsets determined when the equipment was removed by two, thereby assuming an averaged offset over the occupation for processing. Here, "[circle]" refers to the circles visible through the scope of a Sokkia AP41 rotating optical plummet. Although the authors could not find any authoritative information on the angular distance these circles represent, our own measurements lead us to assume the inner circle is ~ 7 arcminutes and the outer circles is ~ 21 arcminutes, which are the values used to calculate the horizontal offset here, given the measured antenna height (DHARP), as 0.5*DHARP*tan(angle). 201A, 36MR, OAKM and ROSA were occupied using a spike mount with a regular level, which was similarly empirically calibrated.*

Site affected	Δe (mm)	Δn (mm)	Reason (from log sheet)
0062	−0.6	−0.6	Mark off by ~ 1/2 [circle] to NE
0114	0.7	0.0	Mark ~ 1/2 [circle] W of center of scope
0409	0.1	0.5	1 mm to 190deg of point [sight]
04LF	0.0	0.7	Mark < 1 [circle] S of scope center
04MD	0.9	2.1	Mark ~ 1.5 [circle] NNE of center of scope
04MF	0.0	−1.7	Mark off by ~ 1 [circle] [to north]
04ND	0.3	−0.7	Mark ~ 1/2 [circle] NNW of scope center
04RS	0.0	−0.7	Mark ~ 1 [circle] off to N
201A	−0.2	0.2	[Level bubble] off by less than 1 mm to the SE direction (i.e. leans to NW direction)
36MR	0.4	0.4	[Level bubble] off center 1 mm to the south west (i.e. leans to NE direction)
502M	0.1	−1.0	Point [Sight] 2 mm to 5deg from marker
BALE	−0.6	−0.6	Mark off by ~ 1 [circle] to NE
DCEC	0.7	0.0	Mark off by ~ 1/2 [circle] to W
DUNC	0.0	−0.3	0.5 mm to S
E480	−0.7	−3.7	Horizontal offset of 7.5 mm to true azimuth 190° and lower height at end

Site affected	Δe (mm)	Δn (mm)	Reason (from log sheet)
FST5	0.2	0.2	Point [Sight] 0.5 mm off at 50° from marker
MDRN	0.5	0.5	Mark < 1 [circle] off to SW
OAKM	−0.5	0.2	[Level bubble] off by 1 mm in the ESE direction" (i.e. leans to WNW direction)
PRH3	0.2	−0.1	Sight ~ 0.5 mm ~ 110° from mark
Q136	−1.4	0.0	Mark ~ 1 [circle] off to E
RFGI	−0.5	0.5	Mark ~ 0.5 [circle] off to SE
RFGO	−0.9	−0.9	Mark ~ 1 [circle] off to NE
ROSA	−0.4	0.4	[Level bubble] half-way between the line and the middle in the SE direction so ~ 1 mm off (i.e. leans to NW direction)
SAPT	0.0	−0.8	Mark ~ 1/2 [circle] N of scope center
SKAG	−1.6	−0.6	Sight 3.5 mm ~ 250° from mark
SKAX	0.5	0.7	Point [Sight] 1.5 mm 040° from marker
VALL	−0.4	−0.4	Mark ~ 0.5 [circle] off to NE

GNSS data processing

Our survey GNSS data, once collated and corrected after the field work, along with data from local continuous GNSS networks, such as the Bay Area Regional Deformation (BARD) Network, were processed using GAMIT/GLOBK 10.7 (Herring et al., 2018) using the latest IGS orbits (repro2). The results were then combined with processed solutions for continuous sites from the Network Of The Americas (NOTA; formerly known as the Plate Boundary Observatory, or PBO) within the surrounding region to generate displacement time series. We inspect these time series for discontinuities and other influential events such as earthquakes. Once these were satisfactorily identified, we used the GAMIT/GLOBK "FOGMEx" algorithm (Floyd and Herring, 2020) to characterize the temporally correlated noise characteristics of each time series from continuous sites contained in the network. Secular velocities are estimated from these time series using a Kalman filter with equivalent random walk process noise to recreate the velocity uncertainties determined in the presence of temporally correlated noise; where necessary (e.g. around the epicenter of the 2014 South Napa earthquake), we account for both coseismic offsets and postseismic transients in this estimation. Finally, we express our velocities and time series in the latest reference frame (ITRF2014/IGS14), rotating these velocities to be relative to the Pacific plate (defined by Altamimi et al.'s, 2017, ITRF2014 Plate Motion Model).

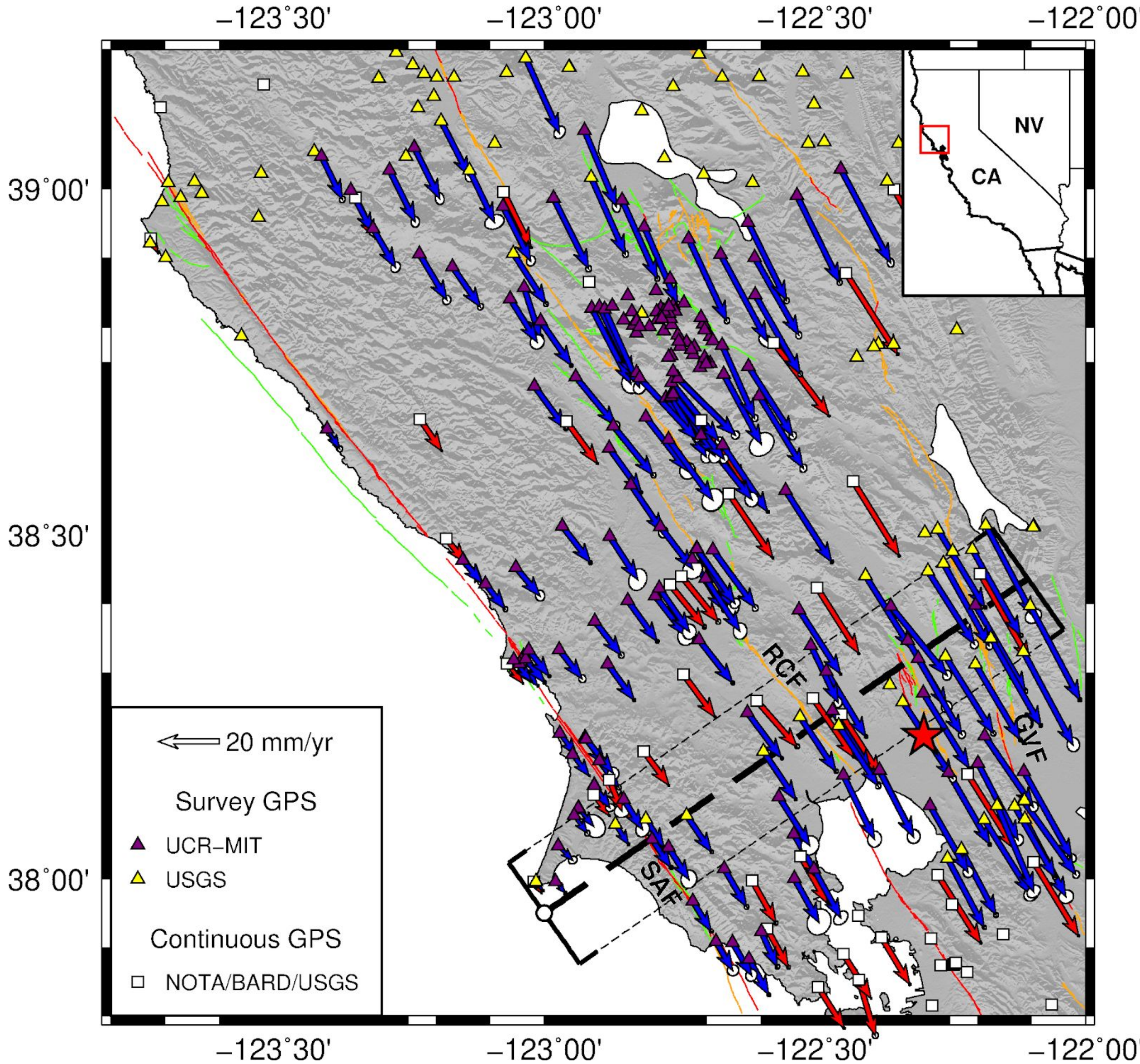

Figure 2 *Latest MIT-UCR velocity solution for the North Bay Area. Solution combines previous surveys conducted throughout the 1990s with those conducted by UCR/MIT since 2008 (blue vectors) as well as the continuous sites in the region with data that are publicly available (red vectors). Velocities are expressed relative to the Pacific plate. Red star marks the epicentre of the 2014-08-24 South Napa earthquake. Dashed line delimits the Point Reyes profile shown in Figure 3.*

Deformation velocities in the northern San Francisco Bay region

As part of our processing efforts, we went back through public archives at UNAVCO, the National Geodetic Survey (NGS) and USGS to incorporate surveys which we had not included before in our processing. This was particularly helpful for improving the density and precision north of San Pablo Bay and the area around the 2014 South Napa earthquake, where the UCR-MIT and USGS survey networks substantially overlap.

Our updated velocity solution, including the survey data collected in 2018, is shown in Figure 2, with a key profile perpendicular to the strike of the major faults in the area, from Point Reyes inland, shown in Figure 3. The key improvement of the velocity solution enabled by the

July-August 2018 survey is to push the velocity uncertainty of many sites from the > 1 mm/yr range to the tectonically-useful < 1mm/yr range, and even below 0.5 mm/yr. Furthermore, the formal incorporation of previous surveys from other institutions has increased the density of our velocity solution, seen by the larger number of survey sites represented by the blue bars in Figure 3 compared to the gray line, which shows the number and distribution of uncertainties in the previous iteration of our velocity solution. However, one significant area of poor coverage remains the Gualala River watershed, between the coastal San Andreas and Maacama faults.

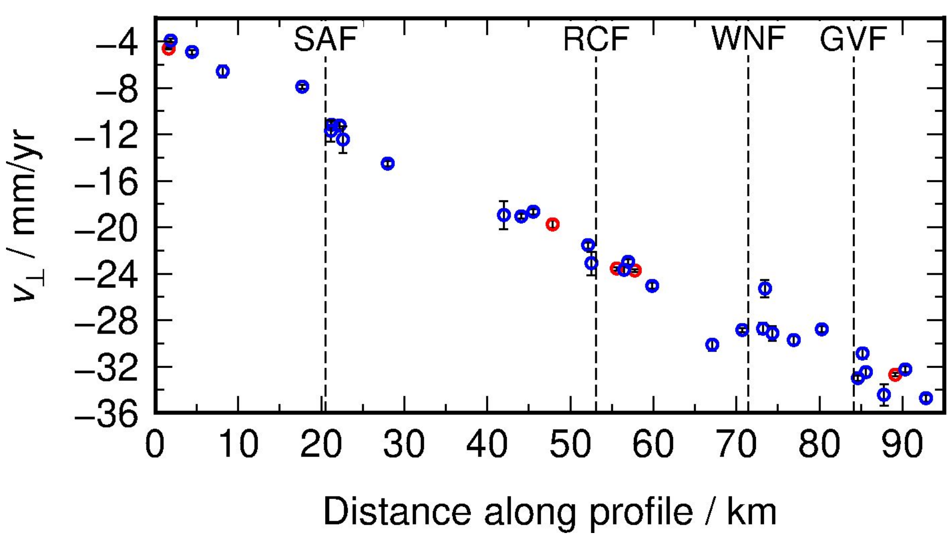

Figure 3 *Profile-perpendicular (i.e. approximately strike-parallel) GNSS velocities along the Point Reyes profile, as shown in Figure 2. Blue dots are survey sites from the UCR-MIT solution and red dots are continuous sites from the NOTA/BARD/USGS networks.*

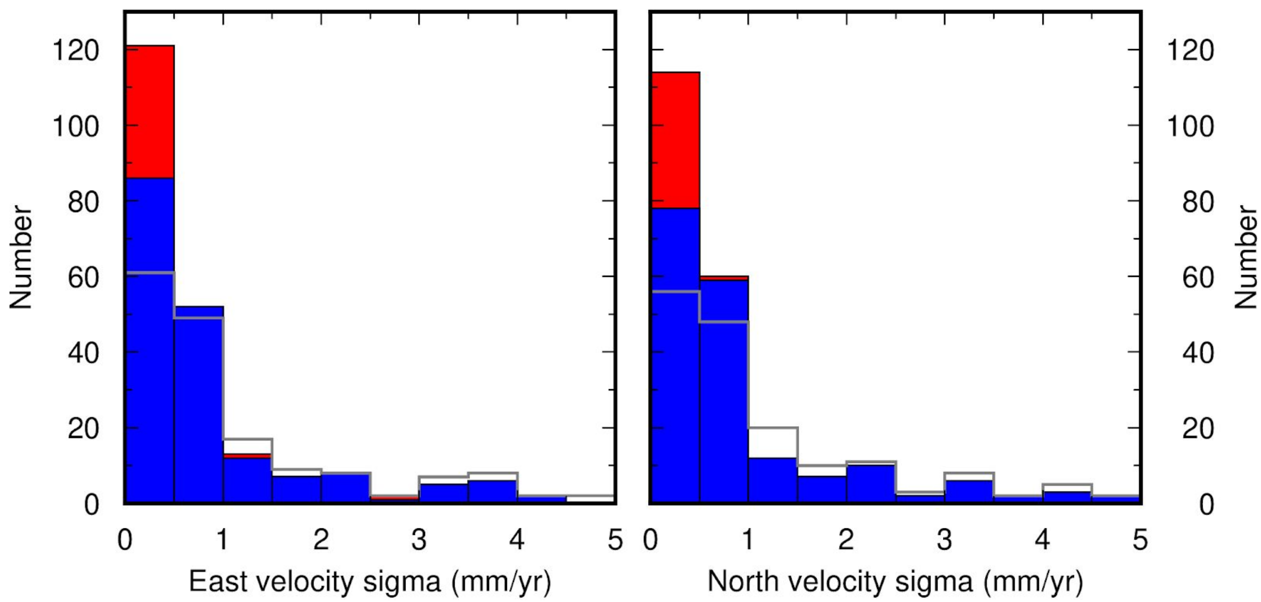

Figure 4 *Distribution of velocity uncertainties after incorporation of the July-August 2018 survey for the same region shown in Figure 2 (excluding The Geysers). Bars show the distribution of site velocity uncertainties in our latest solution, separated by survey (blue) and continuous (red) sites. The gray line shows the distribution of survey (only) site velocity uncertainties from the solution before adding the July-August 2018 survey for comparison. Our velocity solution now includes far more survey sites with uncertainties below a tectonically-useful 1 mm/yr, with most below 0.5 mm/yr.*

Postseismic deformation following the 2014 South Napa earthquake

A second objective for our project was to continue to measure post-earthquake deformation following the M6.0 2014 South Napa event, to build on the work of Floyd et al. (2016), and many others. Several studies at the time detected significant afterslip on the fault plane and, given the fact that many faults in the region creep, we wish to know if the earthquake induced any change in characteristics of the West Napa Fault, including generating creep.

Survey GNSS displacement time series in the epicentral region of the South Napa earthquake are shown in Figure 5. They reveal that rapid afterslip was mostly dissipated by the beginning of 2015, six months after the earthquake, with very little further motion after 2015. Even the closest PBO site, P261, shows no residual motion relative to pre-earthquake velocities from the beginning of 2017 onwards, 2.5 years after the earthquake.

Attendance at the 2019 Northern California Earthquake Hazards Workshop

Both PIs attended the 2019 Northern California Earthquake Hazards Workshop. The poster presented, representing a portion of this report to the date of the workshop, is available at http://geoweb.mit.edu/~floyd/pubs/pdf/2019_USGS_NorCal_Floyd_and_Funning_poster.pdf.

Geodetic response to the July 2019 Ridgecrest earthquakes

Although the M_w6.4 and M_w7.1 Ridgecrest earthquakes in early July 2019 came immediately after the end date of this project (June 30th, 2019), we would be nonetheless remiss if we did not report on the extensive work undertaken by both PIs in collaboration with the USGS in response to the earthquakes.

PI Funning had measured 21 survey sites across the central Mojave Desert with graduate student (Rachel Terry, now at UNAVCO) in February and March 2019, focusing on updating velocities and site positions along the Garlock Fault. That field work was supported by Southern California Earthquake Center (SCEC) Award 18201. After learning of the first (M_w6.4) earthquake, just north of the central Garlock Fault and within the broad region of this recently remeasured network, PI Funning went to the field to make post-earthquake measurements.

Similarly to the PIs' work together before, during and after the 2014 M_w6.1 South Napa earthquake, the survey network augmented the data available from nearby continuous sites and, most importantly, improved the spatial resolution in the near-field: the nearest site to the M7.1 event was survey site PNCL, which was installed as the closest such site (~12 km away) to the M6.4 rupture, but was serendipitously located ~600 m from the southern portion of the M7.1 surface rupture near the Trona Pinnacles when that event occurred. Figure 6 shows the time by which the survey sites were first measured after the earthquakes versus their approximate distances from the fault trace.

Meanwhile, PI Floyd processed the data collected during the two surveys in February and March 2019, as well as post-earthquake data as it was collected from the field, to obtain estimates of coseismic displacements from the survey GNSS data. He also coordinated with the other field teams (two from Scripps Institution of Oceanography, University of California, San Diego, led by Yuri Fialko and Jennifer Haase; and one from the USGS itself, led by Ben Brooks) to organize mutual data exchange and archiving at UNAVCO. The USGS data collection mostly occurred within the Naval Air Weapons Station China Lake, with associated restrictions on field access and data exchange, so we ultimately limited ourselves to working directly with the SIO/UCSD teams. Their data was also incorporated into the processing, presented at the SCEC Annual Meeting (Funning et al., 2019b), and ultimately published as a Data Mine paper in a Focus Section of Seismological Research Letters (Floyd et al., 2020).

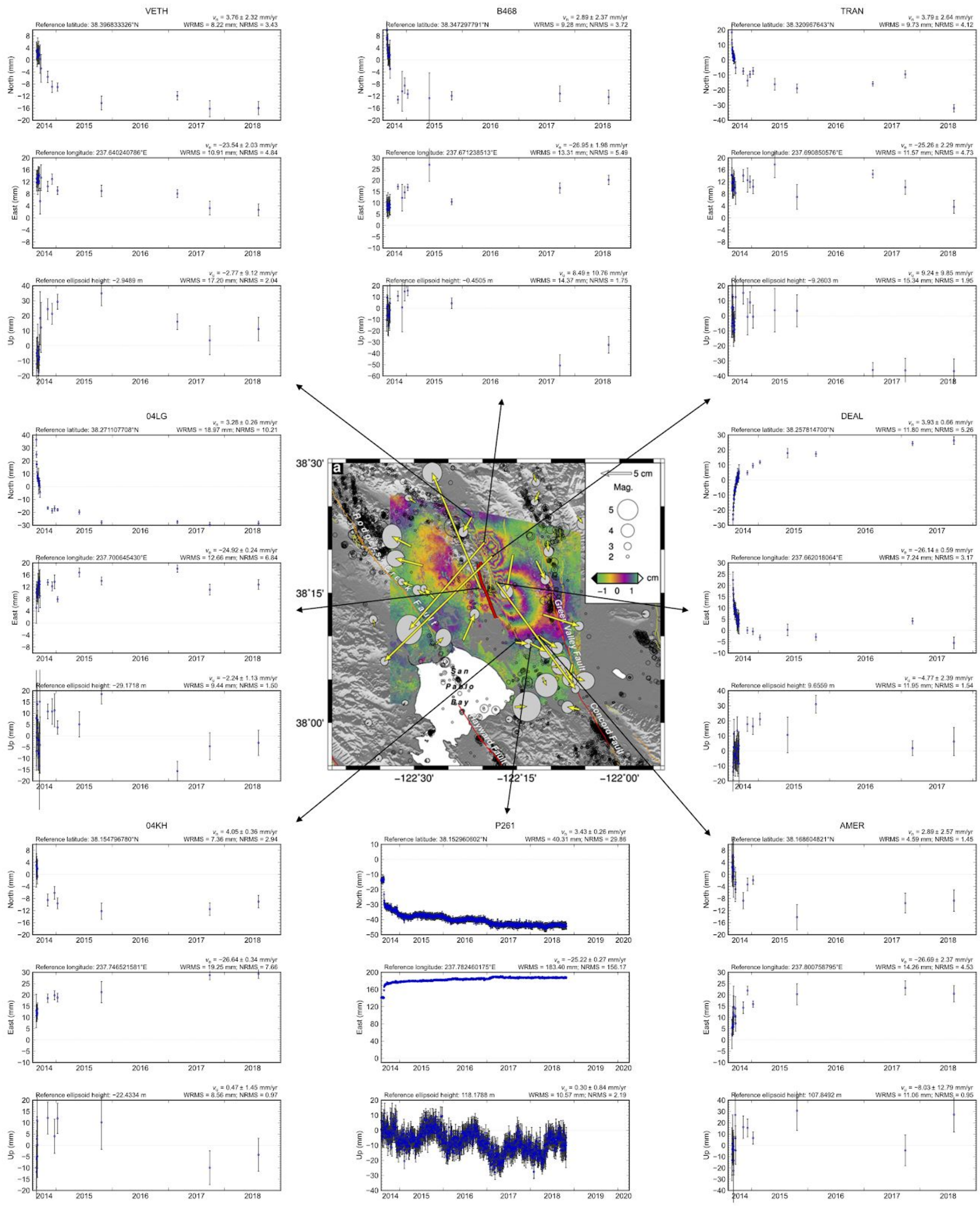

Figure 5 *Time series of post-South Napa GNSS displacements, including the most recent measurements from the July-August 2018 survey. Center map shows InSAR and GNSS displacements of the South Napa earthquake (after Floyd et al., 2016).*

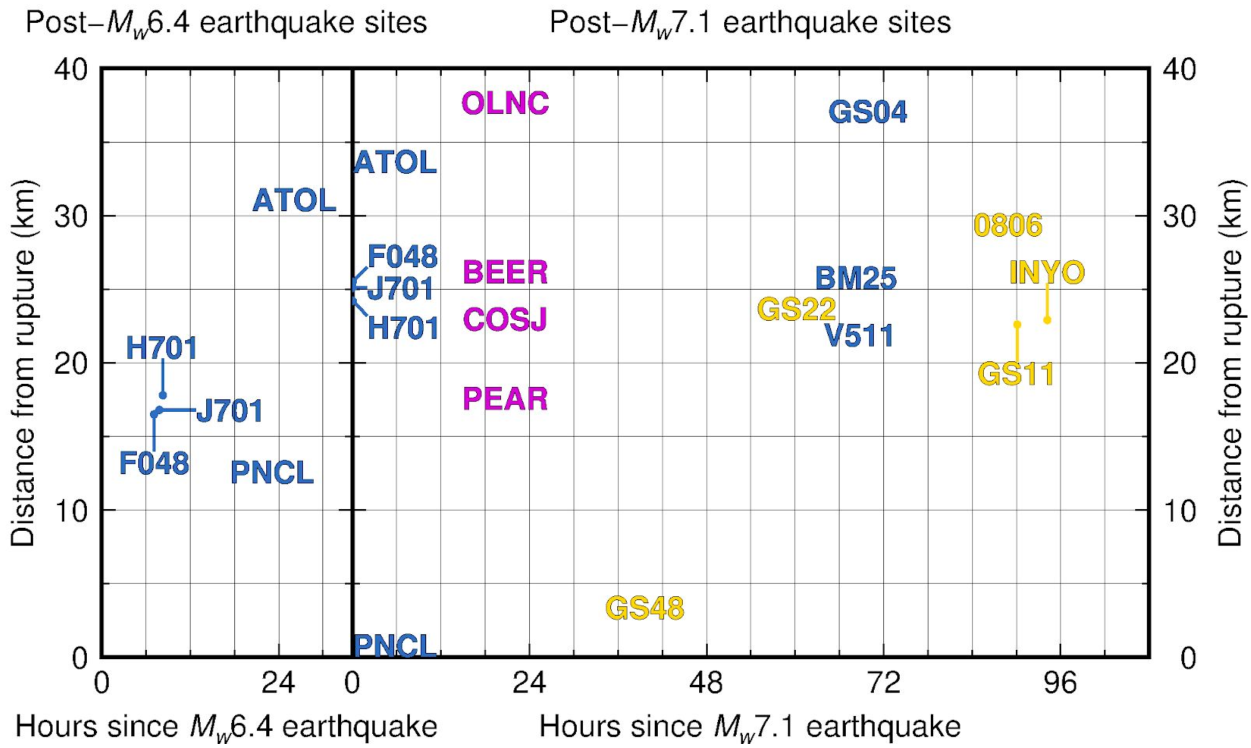

Figure 6 *Details of survey GNSS site occupations in response to the 2019 Ridgecrest earthquakes, arranged by time (horizontal axis) and distance from the nearest fault rupture (vertical axis). Blue site names are sites occupied by the UCR field team, gold site names are sites occupied by researchers from Scripps Institute of Oceanography, and magenta site names are sites occupied by researchers from the Nevada Geodetic Laboratory (Figure S2 from Floyd et al., 2020).*

Summary

During this project, we fulfilled the stated update and improvement of positions in the northern San Francisco Bay Area. We also, due to immediate necessity, prioritized survey data collection in the field and archiving after the July 2019 Ridgecrest earthquakes. All data (raw, RINEX and log sheets) collected during these field surveys in regions of North San Francisco Bay Area (Floyd and Funning, 2019) and the Mojave Desert (Funning et al., 2019a; Fialko et al., 2019) are publicly available at UNAVCO, as required by the project.

We again feel our work has demonstrated the value of continued and focused survey GNSS field work and analysis, for studies over all inter-, co- and post-earthquake parts of the seismic cycle, even in a region that is dominated by networks of long-lived continuous sites. The preparation for responding to eventual earthquakes afforded by projects such as this, conducting field work and processing archived and current survey GNSS data, is a low-cost, high-value undertaking. The work undertaken as part of this project to reprocess and include historic surveys from the archives for both the North Bay and Ridgecrest efforts was significant and we highly recommend that the USGS or UNAVCO consider providing the resources for data processors not only to share their data but to facilitate or store position and velocity solutions in full format, with covariance information (e.g. SINEX), for quick and easy access in the event of a future earthquake response, as noted in Floyd et al. (2020).

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